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BINOCULAR SUMMATION WITHIN THE NERVOUS PATHWAYS OF THE PUPILLARY LIGHT REFLEX

By L. C. THOMSON

From Guy's Hospital Medical School, London

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The question 'Does simultaneous stimulation of the retina of both eyes give rise to a greater response than stimulation of one eye only?' has interested investigators since the last century. Lythgoe & Phillips (1937), who give references to previous authors, measured the change in light threshold during dark adaptation for right, left and both eyes and found that the binocular threshold was lower than the monocular. In both foveal and peripheral vision the binocular threshold was approximately the same as the monocular threshold for a test patch of twice the area, a finding which showed that a moderate degree of summation had occurred when both eyes had been used. Crawford (1940) has repeated the work of Lythgoe & Phillips with substantially similar results and, in addition, has measured the minimum detectable difference of brightness at various brightness levels for both eyes and for a single eye. These measurements showed only a small amount of summation at all brightness levels when the central fovea was used. With the parafovea (8°) two eyes were about 30% more sensitive than one eye to differences of brightness, except at low brightness levels when only a small amount of summation was obtained. Clearly the brightness threshold behaves in a different manner from the light threshold. Crawford gives no explanation of this difference. Pirenne (1943), using a new method of light threshold measurement, has found that there is a small degree of summation in the peripheral retina (20°). He presented several series of 4 m./sec. flashes of light to the eye and for each series determined the number of flashes seen by the observer. The 'frequency of seeing' with both eyes was somewhat greater than that obtained with one eye only, but doubling the intensity of the flashes and observing with a single eye produced a much larger increase in the 'frequency of seeing', and he concluded that under the conditions of his experiment binocular summation was small in amount. Thus it seems that the degree of summation of afferent impulses derived from two eyes depends upon the way in which the effect of these afferent impulses is to be measured. The object of the present experiments was to find out if summation of afferent impulses occurs when a purely objective effect, such as contraction of the pupil, is measured. Since the nervous pathways of the pupillary light reflex do not ascend higher than the mid-brain, the results might help to localize the site of summation within the nervous system.

METHOD

The diameter of the left pupil was measured from photographs of the eye taken with a flash of light of short duration. One or both eyes was exposed to a stimulating flash of known area and intensity and the effect of this flash upon the diameter of the left pupil was determined. The time interval between the stimulating flash and the photographic flash was approximately 0·7 sec. In a preliminary experiment with subject J.P.B.S. it was found that the pupillary response following the stimulating flash was maximal in about 1·5 sec. and thus by using a time interval of 0·7 sec. comparisons could be made during the contraction phase of the response. The diameter of the resting pupil in both subjects was about 7·2 mm. and after 0·7 sec. was about 6·2 mm.

The Ciné-Kodak Special camera, the timing apparatus and a photoflood lamp for taking the flash photographs were all mounted upon a 'gate' which was clamped in front of the subject's chair. The position of the subject's head relative to the camera could be fixed by his biting upon a dental impression mouthpiece attached to the 'gate'. The white stimulating flash was produced by even illumination of the aperture of an iris diaphragm placed at 104 cm. from the eye. The brightness of this aperture was the same for each eye and the flash (0·04 sec. approx.) was produced by a make-and-break switch in the lamp circuit. A small red fixation light was provided, so that the stimulating flash could be viewed either at the central fovea or displaced 8° horizontally into the right visual field. The image of the stimulating flash in the 8° position did not fall upon the blind spot of the right eye. The photographic flash was produced by operating an electromagnetic shutter fitted to the front of a light-tight box containing the photoflood, and this flash had a brightness of 24·6 candles/sq.cm., a duration of 0·04 sec. approx. and an area of 11·68 sq.cm. The image of the illuminated area fell upon the extreme periphery of the retina.

Before any series of experiments, a 15 min. period was allowed for the eye to become dark-adapted. The head was fixed and whilst the subject watched the fixation spot, the camera motor, which was set to take eight pictures a second, was operated and a run completed as follows. The first turn of the camera mechanism (one picture) operated the contact which provided the stimulating flash. During the next five turns the eye was in darkness; on the seventh turn a flash photograph of the left eye recorded the state of the pupil at a time approx. 0·7 sec. later than the end of the stimulating flash. About 0·5 min. sufficed to reset the apparatus and during this time the eye was resting in darkness. A further run was then made.

An experiment was undertaken to determine the effect of the photographic flash upon the resting size of the pupil. Photographs were taken either 0·5 min. or 3 min. after a preliminary photographic flash, and it was found that the pupil diameter was significantly larger at the end of the 3 min. rest than it was after 0·5 min. rest. (Mean diameter of ten measurements of pupil diameter after 3 min. rest, 7·41 mm.; mean diameter after 0·5 min. rest, 7·28 mm.; difference, 0·130 mm. $\pm$ 0·040 mm. standard error.) The rest period of 0·5 min. was chosen because a longer period would have made the experiments very laborious from the subject's point of view, and the failure of the pupil completely to regain the rest position in this time does not destroy the validity of the findings because each run was performed in random order, and therefore each preceding rest period was of random duration, resulting in a random resting pupil size.

At the end of each series of runs a millimetre scale was placed at the focus of the camera system and photographed. Measurements of the pupil diameter were made by projecting the image of this scale photograph on to 0·5 in. graph paper so that 1 mm. equalled 0·5 in. and then by projecting each pupil photograph through the same optical system, this 0·5 in. paper was used to measure the horizontal diameter to the nearest 0·1 mm. The diameter measured was therefore the apparent diameter as seen through the cornea and not the actual diameter.

RESULTS

Preliminary experiments showed that the method was somewhat insensitive. The results in Table 1 show the relationship between the mean pupil diameter and the area of the stimulating flash viewed monocularly. The brightness of

the flash was 0·034 candle/sq.cm. A change of area of the stimulating flash of seventy times resulted in a change of only 0·64 mm. pupil diameter, and, if the use of both eyes were equivalent to doubling the area of the stimulating flash and using one eye, then it is clear that to increase precision a large number of runs would be required, with the results treated statistically.

TABLE 1. The relationship between the pupil diameter and the area of the stimulating flash observed with one eye only

Area of stimulating flash (sq.cm.)	Pupil diameter (mm.)			Mean (mm.)
28·1	6·2	5·8	5·8	5·93
17·8	6·0	5·8	5·9	5·90
13·8	6·5	6·0	6·0	6·17
8·0	6·2	6·4	6·0	6·20
3·7	6·2	6·2	6·2	6·20
0·4	6·6	6·5	6·6	6·57

Accordingly, the experiments were built on the following plan. A series of triplets was performed. (i) A run using the standard area viewed with one eye. (ii) (*a*) Double, or (*b*) four times the area viewed with one eye. (iii) The same standard area as in (i) viewed with two eyes. Within the triplet the runs were presented to the observer in random order. From each triplet three pupil diameters were obtained and that for treatment (i) was compared with that for (ii) or (iii). The diameter of each (ii) or (iii) was subtracted from the corresponding (i) and thus from each series of triplets a number of differences was available for each of the two comparisons. If, in fact, runs (i) and (ii) and runs (i) and (iii) produced the same result, the mean of these differences would on the average be zero. A series of twenty-seven triplets gave the differences shown in Table 2 for the (i)–(iii) comparison. The mean difference is +0·185 mm.

TABLE 2. Twenty-seven differences of pupil diameter (mm.) obtained by comparing the figures for monocular and binocular tests

0·0	−0·6	−0·1
+0·3	+0·4	+0·2
+0·1	+0·4	+0·3
+0·4	0·0	+0·8
−0·1	0·0	+0·1
+0·4	+0·5	+0·4
+0·1	+0·1	+0·2
0·0	+0·1	0·0
0·0	+0·8	+0·2

with a standard error of ±0·055 mm. This mean difference could have arisen either as the result of random experimental variations or as a significant difference of effect between treatments (i) and (iii). To decide between these two possibilities 'Student's' distribution of t was used and in this case it was found that a mean difference as large, or larger, than this would on the average occur by chance in one out of every 500 series of twenty-seven differences and it was therefore extremely unlikely that this particular set of twenty-seven differences arose as the result of random experimental variation. Thus in this

case the mean difference +0·185 mm. indicates a significant difference of effect between the monocular and binocular runs.

The standard error ±0·055 mm. includes such errors as those due to variations in the duration of the stimulating flash as well as those due to the variations in the response of the nervous pathways and although no precise evaluation of the relative magnitude of these errors was made, the instrumental and measuring errors appeared insignificant beside the variation in the response of the nervous pathways. The value of this experimental design is that the significance of the result can be judged in the face of both instrumental and biological errors, because the standard error, as here calculated, is a measure of the total experimental error.

Table 3 shows the results for two subjects for the comparison between monocular and binocular runs. Several series of triplets have been attempted and if 1 in 20 is taken as the level of significance, all except one series clearly show binocular summation. The stimulating flash had a brightness of 0·0060 candle/sq.cm. for the parafovea and 0·0053 candle/sq.cm. for the central fovea. It subtended an angle of 39·6′ at the eye for the standard area. No direct comparison between the degree of summation at the central fovea and that at the parafovea was made, but from the figures in Table 3 it seems unlikely that the difference of behaviour is great.

Table 4 gives the relationship between the mean monocular-binocular difference and the mean difference between runs in which the standard area (visual angle 39·6′) and runs in which twice (56′) and four times (1° 19′) the area were used. Mean differences in any one line are comparable because the differences from which they have been calculated were obtained from the same series of triplets, but owing to day-to-day variation one line cannot be compared with another in the same certainty.

The difference between the two mean differences in any one line is given in column Δ with the appropriate standard error in column σ_Δ. 'Student's' distribution of t was used to test whether or not each Δ could be regarded as significant and this for each Δ (level 1 in 20) is recorded in the final column of the table. The probability in lines 1 and 2 was obtained by graphical interpolation in the table of t and since the Δ in line 1 only just failed to reach significance and was in the same sense as that in line 2, a further test was undertaken which treated lines 1 and 2 as a whole. The χ^2 distribution was used and it was determined whether two probabilities as low as those in lines 1 and 2 would be likely to occur by chance in two tests of significance of the same phenomenon. χ^2 was 13·87 for four degrees of freedom and this value is only equalled or exceeded by chance in less than one case in a hundred, so that the Δ's in lines 1 and 2 are clearly significant if considered together.

Thus for the parafovea of subject T.E. the increase of constriction obtained with binocular instead of monocular vision was greater than the increase

TABLE 3. The relationship between the mean pupil diameters found in monocular and binocular tests

		Central fovea						Parafovea (8°)			
Date	Subject	No. of diff.	Mean diff. (mm.)	σ_{mean}	Probability	Date	Subject	No. of diff.	Mean diff. (mm.)	σ_{mean}	Probability
1. vi. 46	T.E.	25	+0·160	±0·029	<0·001	31. v. 46	T.E.	25	+0·052	±0·037	<0·20
						27. vi. 46	T.E.	25	+0·320	±0·049	<0·001
						27. vi. 46	T.E.	25	+0·236	±0·033	<0·001
4. vi. 46	J.P.B.S.	20	+0·320	±0·048	<0·001	25. iv. 46	J.P.B.S.	27	+0·185	±0·055	<0·01
						1. vii. 46	J.P.B.S.	18	+0·228	±0·087	<0·02

TABLE 4. The relationship between the increase of constriction of the pupil obtained when two eyes were used instead of one, and the increase found when the area of the stimulating flash was increased whilst observing with a single eye

(All figures in this table have been approximated to three places of decimals.)

			Monocular area × 2			Binocular						
	Date	Subject	No. of diff.	Mean diff. (mm.)	σ_{mean}	No. of diff.	Mean diff. (mm.)	σ_{mean}	Δ	σ_{Δ}	Probability	Significance
(1)	27. vi. 46	T.E. (8°)	25	+0·196	±0·041	25	+0·320	±0·049	0·124	±0·064	0·059	No
(2)	27. vi. 46	T.E. (8°)	25	+0·100	±0·044	25	+0·236	±0·033	0·136	±0·055	0·017	Yes
(3)	25. iv. 46	J.P.B.S. (8°)	23	+0·009	±0·040	27	+0·185	±0·055	0·176	±0·067	<0·020	Yes
			Area × 4			Binocular						
(4)	31. v. 46	T.E. (8°)	25	+0·160	±0·048	25	+0·052	±0·037	0·108	±0·060	<0·100	No
(5)	1. vi. 46	T.E. (fovea)	24	+0·258	±0·033	25	+0·160	±0·029	0·098	±0·046	<0·050	Yes
(6)	4. vi. 46	J.P.B.S. (fovea)	20	+0·290	±0·051	20	+0·320	±0·048	0·038	±0·070	<0·700	No

obtained by doubling the area and observing with a single eye and this was also true for the parafovea of J.P.B.S. (line 3). In the parafovea of T.E. the binocular increase might be as great as that produced by increasing the area four times (line 4), but this was not so when this subject used the central fovea (line 5). In the central fovea of J.P.B.S. (line 6), on the other hand, the degree of summation corresponds well with an areal increase of four times in the single eye.

Owing to the considerable repetition of the runs, the subjects could find out from the small noises made in resetting the apparatus which type of stimulating flash they were about to see, and this knowledge might have influenced the result. To test this possible cerebral interference, a further experiment with subject J.P.B.S. was made using the parafovea. Precautions were taken to prevent the subject from finding out which flash he would see next and the success of these precautions was tested by asking him to say, just before taking a bite, which flash he thought would be the next. Runs were of four kinds, the standard area being used throughout. (*a*) Viewed with one eye and unknown to the subject. (*b*) Viewed with two eyes and unknown. (*c*) Viewed with one eye and known. (*d*) Viewed with two eyes and known. In the 'known' runs the subject was told which type of flash he would see. All four types were performed in random order. Out of the thirty-six runs in types (*a*) and (*b*) the subject declared correctly nineteen times and incorrectly seventeen times and since the chance was 1 in 2, the precautions taken to ensure that the runs were 'unknown' were satisfactory. Binocular summation was again found when runs (*a*) and (*b*) were compared ($+0{\cdot}228$ mm. $\pm 0{\cdot}087$ mm.) but a significant result was not obtained with runs (*c*) and (*d*) ($+0{\cdot}106$ mm. $\pm 0{\cdot}104$ mm.). It seems that if the attention of the subject is definitely directed to the type of run to be performed, a somewhat larger error will result and since an error as large as $\pm 0{\cdot}104$ mm. had not previously been found, cerebral activity is unlikely to have influenced the results in the tables.

DISCUSSION

The afferent neurons of the light reflex run from the retina to the pretectal nucleus in the mid-brain where synapses are formed with short connector neurons, themselves forming synapses with the neurons of the Edinger-Westphal portion of the oculomotor nucleus. From here the motor fibres pass via the oculomotor nerve to the constrictor muscle of the iris. Since these pathways do not utilize co-ordinating neurons above the level of the mid-brain, the binocular and areal summation found in these experiments probably occurs at the synapses within either the pretectal or oculomotor nucleus. It is thus possible that the binocular summation found with dark-adaptation threshold measurements occurs at a level below that of the cerebral cortex, perhaps in the lateral geniculate body.

SUMMARY

1. It has been shown that the degree of constriction of the pupil which results from the stimulation by light of the retina of a single eye was significantly less than that obtained when both eyes were stimulated.

2. This binocular summation was equivalent to that obtained by increasing the area of the stimulating flash between two and four times and observing with a single eye throughout.

3. This binocular summation does not appear to be influenced by cerebral cortical activity and the position of the summation within the nervous pathways is discussed.

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REFERENCES

Crawford, B. H. (1940). *Proc. Roy. Soc.* B, **128**, 552.
Lythgoe, R. J. & Phillips, L. R. (1937). *J. Physiol.* **91**, 427.
Pirenne, M. H. (1943). *Nature, Lond.*, **152**, 698.